NUMERICAL SIMULATION AND VISUALIZATION FOR BUILDING ENVELOPE THERMAL DISTRIBUTION ANALYSIS

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ABSTRACT: *Over the past decade, growing concerns regarding global warming and energy supply problems have raised social awareness of energy conservation and carbon reduction, leading to green buildings emerging as a growing trend in building design and engineering. There are four main strategic areas for developing energy-saving buildings: (i) building envelopes, (ii) heating, ventilation and air-conditioning (HVAC), (iii) lighting and (iv) equipment. Among these, building envelopes have played the most significant role. If energy-saving strategies are considered when designing a building, low energy consumption and carbon dioxide emissions of the building can be expected. For example, reduced use of HVAC and lighting equipment can be achieved by simply considering the interaction between the building envelope and the surrounding environment, such as ventilation, sunshade, and ambient lighting. In this research, we focus on the thermal distribution of the building envelope. This research also develops a visual simulation system carried out in the MicroStation Visual Basic for Applications (MVBA) environment. The proposed numerical model was implemented in the visual simulation system for assisting planners in calculating the thermal distribution of the building envelope. This system provides a visual environment for presenting analyzed data and visualization models, and also assists planners in finding and utilizing relevant and necessary data in a more direct and efficient manner to achieve a good energy-saving design in the early stages of any building project, or to validate the final product design.*

KEYWORDS: *Numerical Simulation, Visualization, Solar Radiation, Thermal Distribution, Building Envelope*

1. INTRODUCTION

Currently, global warming and energy supply are set to be important issues in our lives, which is why many researchers have become more concerned about the concept of green buildings, sustainable buildings and low-energy houses [Satterfield, 2009; Karlsson et al., 2006], with green buildings emerging as a growing trend in building design and engineering. The concept of a “green building” is primarily driven by the objective of fully harnessing available resources to reduce pollution, creating the best possible environment with the least resources [Chang et al., 2011]. In the past, air-conditioning design-calculation focused on the estimation of peak loads which were determined either by manual calculation or simple computing methods. Nowadays, load calculation has not only become more complicated but there are also requirements to conduct energy analysis at the building’s design stage [Hui et al., 1998]. However, the heat exchange process in buildings is an unsteady state and consequently varies in time. Volatility of the heat exchange process is influenced by oscillating external temperature, internal heat gains, solar radiation and other factors that affect the heat balance of a building [Pupeikis et al., 2010]. Because solar radiation is a major contributor to the heat gain of a building, accurate estimation of solar radiation on the envelope of a building is required in many applications. For example, higher solar radiation received implies greater total solar heat gain and hence higher energy requirements for cooling. In designing an air conditioning system, knowledge of the total radiation striking a surface over a specified period of time is required [ASHRAE, 2009]. There are many ways to predict solar radiation [Bird et al., 1981; ASHRAE, 2009]. The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) proposed a clear-sky radiation model to calculate the solar radiation on building surfaces. To design an air conditioning system, the equipment is sized for operation when the building is subjected to high solar radiation. A clear sky allows a high level of solar radiation to reach the earth and the ASHRAE uses a clear sky model for estimating the hourly irradiation on the earth’s surface [Wessapan et al., 2008]. In this research, we focused on how solar radiation influences the thermal distribution of the building envelope, because solar radiation is the main influence on the thermal balance of a building. By analyzing thermal situations and improving them at the design stage, much energy can be saved because the requirements on cooling equipment can be reduced. To achieve this, this research developed a visual thermal distribution simulation system for analyzing and visualizing solar radiation of a building envelope. All of the application functions were implemented on the Bentley MicroStation. This system assists planners in identifying and understanding the possible blind spots affecting the achievement of energy-saving requirements of the designed buildings, and enables further design modifications to optimize energy-saving effects.

2. PROPOSED METHODOLOGY

With a global revolution in process towards the creation of a greener environment, there is increasing impetus to avoid energy waste and reduce carbon emissions. Solar radiation is responsible for most of the heat gain of a building. In this study, we developed a visual simulation system which can assist planners to calculate the thermal distribution of a building envelope. Figure 1 shows the flowchart of the proposed methodology for analyzing the solar radiation on a building envelope. The four step sequence presented in the flowchart is an important aspect of this study. Before analysis of solar radiation, the 3D model and numerical model should be ready for analysis and visualization. The new ASHRAE clear-sky radiation sky model of 2009 has three criteria during the selection and development process: accuracy, universality, and ease of use [Thevenard, 2009]. Firstly, a planner needs to specify the building envelope and define the grid size in the grid generation module. The grids will be generated according these settings for accurate calculation of thermal distribution on the surface. Secondly, the system will calculate the value of solar radiation using the numerical equation of the ASHRAE clear-sky model. In this research, the ASHRAE clear-sky model is used to estimate the monthly solar radiation on different slopes of different surfaces. However, different areas have their local climate characteristics and parameters. For accurate determination of solar radiation values, the latitude and longitude, local time-zone and local parameters of the building are needed for input into the model. To use the model at other locations to calculate the solar radiation values, it is necessary to adjust the atmospheric extinction coefficient and the diffuse radiation factor of the local sky, known as the model parameters, because of their local sky conditions [Wessapan et al. 2008]. Therefore, the database is also used for collecting climate parameters and area data in different regions. The system calculates the beam ($E_{t,b}$), diffuse ($E_{t,d}$) and ground-reflected ($E_{t,r}$) solar radiation components of each grid surface. Following this, the system will analyze the total solar radiation received on the surface of the building envelope. Finally, the system will apply color schema to visualize the result of solar radiation calculations. A good visual representation of data can assist people in efficiently acquiring applicable information. Therefore, planners will be able to better understand the status of thermal distribution of the building envelope from this system, and then proceed to redesign or improve building design to achieve an effective energy-saving building.

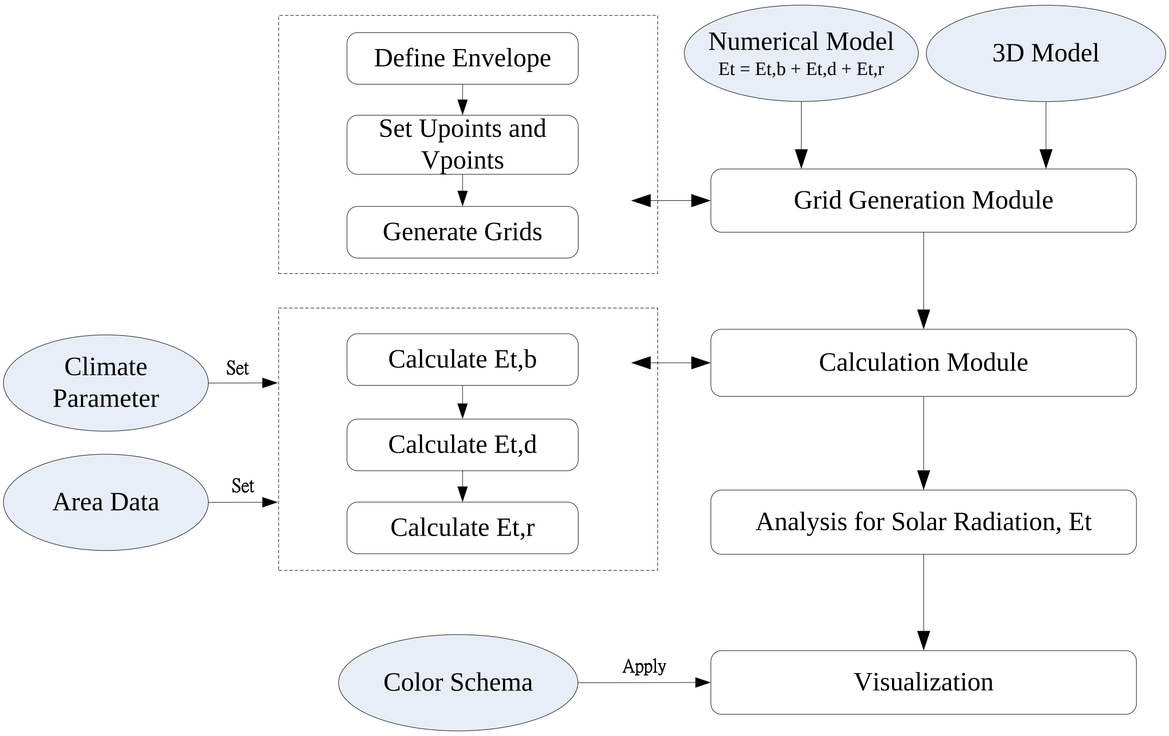


Figure 1: The flowchart of the proposed methodology.

3. NUMERICAL MODEL

In order to design an energy-saving building, we need to know the incident solar radiation on an envelope of the building. This is because solar radiation is a major factor for a building's heat gain. When the sky is clear, the building's heat gain is mainly from solar radiation. And we know the ASHRAE has a clear-sky model for estimating the solar radiations on a clear day. McQuiston et al. commented that the ASHRAE clear-sky model is commonly used as a basic tool for solar heat load calculation of air conditioning systems and building designs [McQuiston et al. 2010]. Therefore, we employed ASHRAE clear-sky model to calculate solar radiation of building envelope in this research.

Clear-Sky Radiation Model

Solar radiation is a major contributor to the heat gain of a building. As shown in equation (1), the total clear-sky irradiance Et reaching the receiving surface is the sum of three components: the beam component $E_{t,b}$ originating from the solar disc; the diffuse component $E_{t,d,}$ originating from the sky dome; and the ground-reflected component $E_{t,r}$ originating from the ground in front of the receiving surface [ASHRAE, 2009].

$Et = E_{t,b} + E_{t,d} + E_{t,r}$…… (1)

Air Mass

The relative air mass m is the ratio of the mass of atmosphere in the actual earth/sun path to the mass that would exist if the sun were directly overhead. This is represented by

$m = 1/ [\sin \beta + 0.50572(6.07995 + \beta)–1.6364]$…… (2)

where β is expressed in degrees.

Clear-Sky Solar Radiation

Solar radiation on a clear day is defined by its beam (direct) and diffuse components. The direct component represents the part of solar radiation emanating directly from the solar disc, whereas the diffuse component accounts for radiation emanating from the rest of the sky. These two components are calculated as

$E_b = E_o \exp [–\tau_b mab]$…… (3)

$E_d = E_o \exp [–\tau_d mad]$…… (4)

where: E_b = beam normal irradiance (measured perpendicularly to rays of the sun), E_d = diffuse horizontal irradiance (measured on horizontal surface), E_o = extraterrestrial normal irradiance, m = air mass, τ_b and τ_d = beam and diffuse optical depths, ab and ad = beam and diffuse air mass exponents.

Air mass exponents ab and ad are correlated to τ_b and τ_d through the following empirical relationships:

$ab = 1.219 – 0.043\tau_b – 0.151\tau_d – 0.204\tau_b\tau_d$……(5)

$ad = 0.202 – 0.852\tau_b – 0.007\tau_d – 0.357\tau_b\tau_d$……(6)

Beam component, $E_{t,b}$

The beam component is obtained from a straightforward geometric relationship:

$E_{t,b} = E_b \cos \theta$ ……(7)

where θ is the angle of incidence. This relationship is valid when $\cos \theta > 0$; otherwise, $E_{t,b} = 0$.

E_b= beam normal irradiance (measured perpendicularly to rays of the sun)

Diffuse Component, $E_{t,d}$

The diffuse component is more difficult to estimate because of the non-isotropic nature of diffuse radiation: some parts of the sky, such as the circumsolar disc or the horizon, tend to be brighter than the rest of the sky, which makes the development of a simplified model challenging. For vertical surfaces, Stephenson (1965) and Threlkeld (1963) showed that the ratio Y of clear-sky diffuse irradiance on a vertical surface to clear-sky diffuse irradiance on the horizontal is a simple function of the angle of incidence:

$E_{t,d} = E_d Y$…… (8)

with $Y = \max(0.45, 0.55 + 0.437 \cos\theta + 0.313 \cos^2\theta)$…… (9)

For a non-vertical surface with slope Σ, the following simplified relationships are sufficient for most applications described in this volume:

$E_{t,d} = E_d(Y \sin\Sigma + \cos\Sigma)$ if $\Sigma \leq 90°$…… (10)

$E_{t,d} = E_d Y \sin\Sigma$ if $\Sigma > 90°$…… (11)

where Y is calculated for a vertical surface having the same azimuth as the receiving surface considered.

Ground-Reflected Component, $E_{t,r}$

Ground-reflected irradiance for surfaces of all orientations is given by

$E_{t,r} = (E_b \sin\beta + Ed)\rho_g(1 - \cos\Sigma)/2$…… (12)

where ρ_g is ground reflectance, often taken to be 0.2 for a typical mixture of ground surfaces.

Example

In Kaohsiung (southern Taiwan), direct, diffuse and ground-reflected components of solar irradiance are calculated on July 21 at noon, solar time. We assume that the azimuth of the receiving surface is 60°, θ=88.886°. Table 1 provides astronomical data for the calculation.

$E_{t,b} = E_b \cos\theta = 15.534$

$E_{t,d} = E_d Y = 97.755$

$E_{t,r} = (E_b \sin\beta + Ed)\rho_g(1 - \cos\Sigma)/2 = 97.339$

$E_t = E_{t,b} + E_{t,d} + E_{t,r} = 15.519 + 97.893 + 97.276 = 210.628$

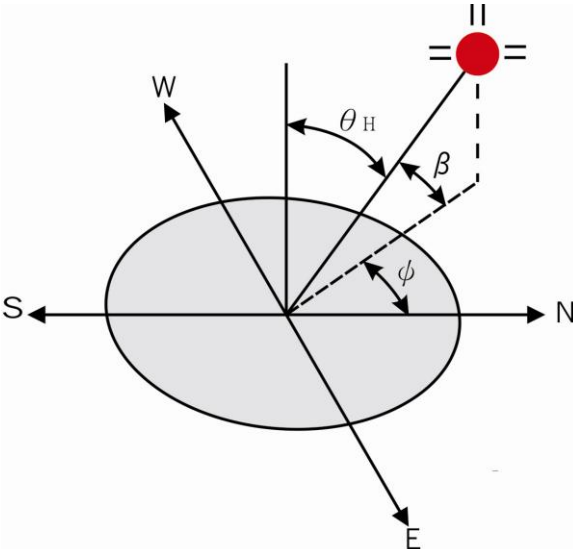


Figure 2: Solar angler for surfaces

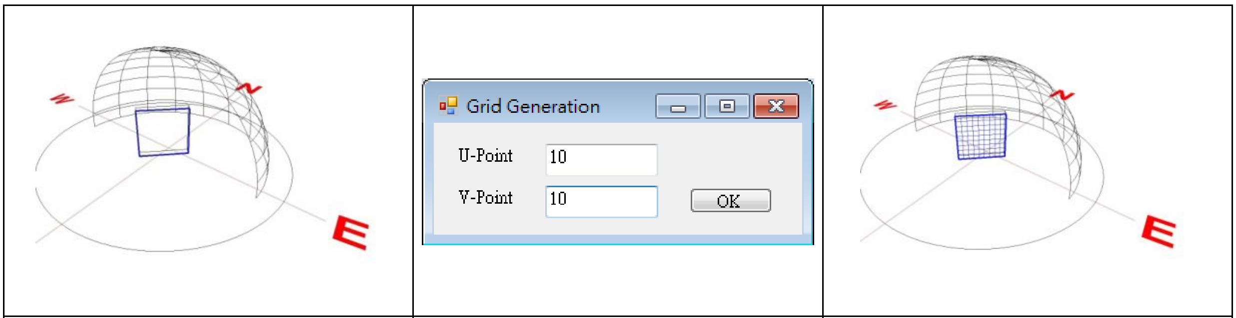
Table 1: Astronomical data for Kaohsiung city

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
E_o,w/m^2	1410	1397	1378	1354	1334	1323	1324	1336	1357	1380	1400	1411
Declination(δ)	-20.1	-11.2	-0.4	11.6	20.1	23.4	20.4	11.8	-0.2	-11.8	-20.4	-23.4
τ_b	0.579	0.613	0.753	0.690	0.568	0.552	0.506	0.560	0.575	0.632	0.596	0.548
τ_d	1.644	1.601	1.423	1.542	1.813	1.870	2.022	1.845	1.790	1.628	1.655	1.723

Lat: 22.63N Long: 120.28E Time Zone: GMT+8

4. GRID GENERATION AND ANALYSIS

Automatic mesh generation (grid generation) has become an essential tool for the finite element or finite volume analyses of practical engineering problems [Lee et al., 2010]. This research takes advantage of automatic grid generation for analyzing and visualizing the thermal distribution of the building envelope in detail. The system generates numerous grids according to the building envelope in a 3D model for representing and analyzing the heat gains. The grid size is defined by the user according to the level of precision they need. The processes of grid generation are shown in Figure 3. Firstly, the user needs to specify the building envelope of the 3D model whose surface is heated by solar radiation directly. At this step, a facet of the 3D model which the user wants to analyze can be extracted. The user then defines numbers of U-points and V-points for determining the grid size which will decide the precision of analysis. The U-direction is the direction in which the data points that defined each row were entered; the V-direction is the direction in which the columns were defined. Next, the system will generate grids according to the user's settings. Finally, the system will calculate the solar radiation for each grid by the above-mentioned numerical model. In the numerical model, the slope of each facet will affect the calculation of solar radiation because different slope will mean different levels of reception of sunshine, such as 0° for the floor, 45° for the roof and 90° for a wall, as shown in Figure 4. The calculated results (shown in Table 2) show that different slopes are differently affected by the sun. The system will then apply color schema to visualize the result of differential solar radiation received. Following this, we can easily determine how solar radiation influences the thermal distribution of building envelope.



Step 1: Specify building envelope	Step 2: Define U-points and V-points	Step 3: Generate grids

Figure 3: The processes for grid generation

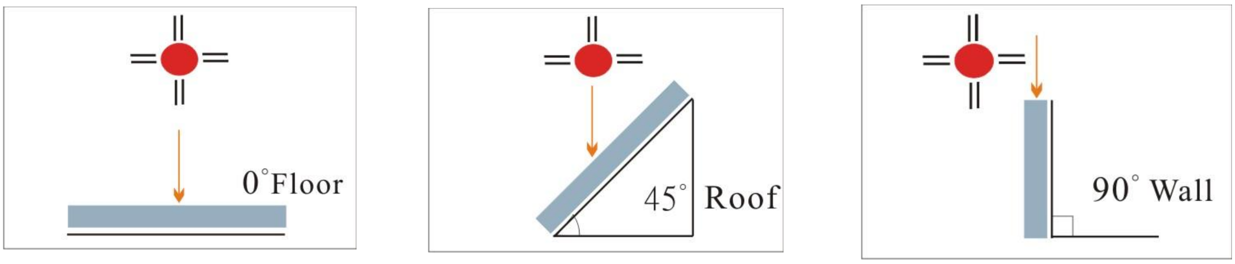


Figure 4: The interactions between solar radiation and slope on the building envelope

Table 2: Parameters for different slopes of building envelope in Kaohsiung city

Slope	$E_{t,b}$ (w/m^2)	$E_{t,d}$ (w/m^2)	$E_{t,r}$ (w/m^2)	E_t (w/m^2)
0°	798.395	227.395	0	1025.790
45°	575.623	250.863	28.510	854.996
90°	15.534	97.755	97.339	210.628

5. NUMERICAL SIMULATION FOR ENVELOPE THERMAL DISTRIBUTION ANALYSIS

5.1 SYSTEM FRAMEWORK

The visual thermal distribution simulation system is developed based on the Building Information Model which includes a 3D model, climate parameters, time, and area data. The implementation of the system was carried out in the MicroStation Visual Basic for Applications (MVBA) environment. The Bentley MicroStation supports visualization of the 3D building model and provides some capabilities for 3D object manipulation and information query. Application Programming Interfaces (APIs) are also provided for functionality extensions. The system has four main modules, which are described as follows: (1) Parameter Configuration: this module provides functions to assist the user with configuring the relevant parameters; (2) Grid Generation Module: the user can specify the building's envelope and grid size for grid generation; (3) Calculation Module: this module calculates the required value for solar radiation according to input data; (4) Analysis for Solar Radiation: this module is responsible for analyzing the result of the solar radiation calculation. Finally, the system will apply the specific color schema to visualize the result of solar radiation analysis for the user to easily understand the thermal distribution of building's envelope.

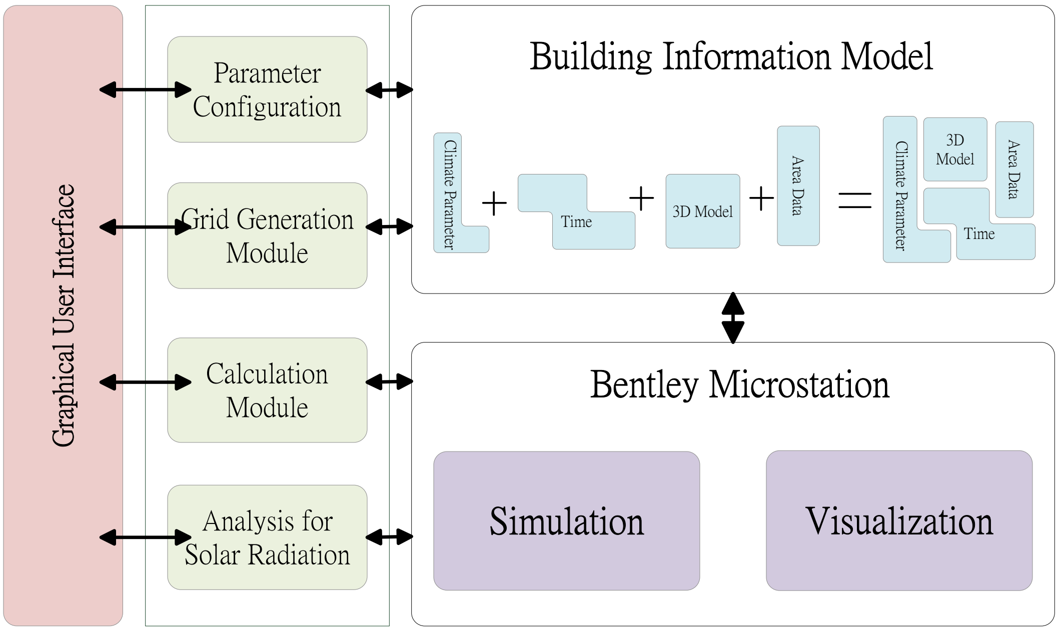


Figure 5: System framework for visual thermal distribution simulation system

5.2 Example

Figure 6 illustrates the main graphical user interface (GUI) of the visual thermal distribution simulation system. Five functionalities are provided to the user: (1) Project, (2) Setting, (3) Grid Generation, (4) Calculation, and (5) Analysis. In this section, we demonstrate the system using a simple model for testing. Firstly, planner creates a new project and configures the related information, such as project name, location, time zone and building data; the system will retrieve the required data from the database for calculation and analysis (see Figure 7(a)). Secondly, the planner will specify the surface of the building envelope and define numbers of U-point and V-point for grid generation (as shown in Figure 7(b)). Grids size will affect the precision of solar radiation calculation. Next, the system will calculate the beam ($E_{t,b}$), diffuse ($E_{t,d}$) and ground-reflected ($E_{t,r}$) solar radiation components for each surface of grid using the calculation module. The system will then analyze the total solar radiation for each building envelope and display the results using a tree view, as shown in Figure 7(c). The planner can then click the tree-node of the particular building envelope to view the related information. Finally, the system will apply color schema to visualize the result of solar radiation, as shown in Figure 7(d). The 3D objects in the building model are highlighted in different colors depending on their thermal distribution statuses. Table 3 shows the color scheme implemented in this work.

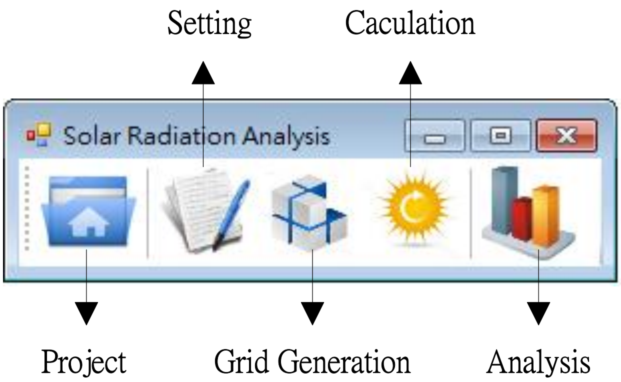
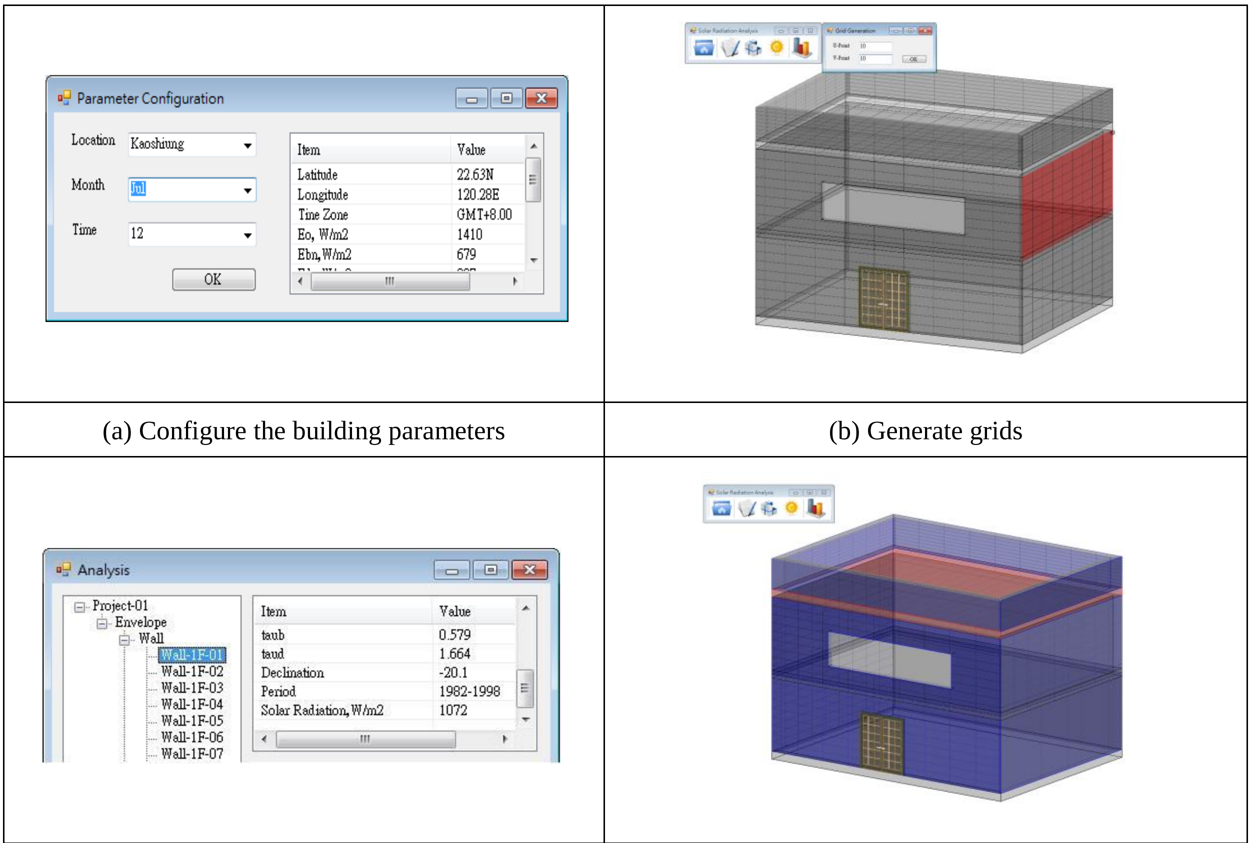


Figure 6: Graphical User Interface

Table 3: Color schema for solar radiation analysis

Color		Solar Radiation
	Blue	200 ~ 400 (W/m^2)
	Green	400 ~ 600 (W/m^2)
	Yellow	600 ~ 800 (W/m^2)
	Orange	800 ~ 1000 (W/m^2)
	Red	>1000 (W/m^2)



(a) Configure the building parameters

(b) Generate grids

(c) Calculate solar radiation

(d) Visualize the value of solar radiation on surface

Figure 7: Example of visualization of solar radiation of a building

6. CONCLUSIONS AND SUGGESTIONS

The thermal distribution of a building's envelope is a key factor in building design, affecting the use of energy for air-conditioning. Due to the long-term outdoor exposure of a building to solar radiation, its indoor temperature can be significantly affected. If a planner can understand the building's thermal distribution at early stage of design, aspects such as ventilation design can be improved to reduce heat gain of a building's envelope and ultimately reduce usage of air-conditioning. A visual thermal distribution simulation system was developed in this research to facilitate planners' understanding of buildings' thermal distribution at the early stages of development. This enables planners to detect thermal issues early, provide feedback and make adjustments in order to achieve a green, energy-saving building. A simple model was used as an example to demonstrate the workings of the system. In future work, synthetic considerations will be made of the three heat transfer modes: (i) air convection, (ii) radiation through windows and doors, and (iii) heat conduction between the building materials, to calculate the thermal distribution more accurately.

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